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## ASSESSING THE STRATIGRAPHIC INTEGRITY OF PLANKTIC AND BENTHIC $^{14}\text{C}$ RECORDS IN THE WESTERN PACIFIC FOR $\Delta^{14}\text{C}$ RECONSTRUCTIONS AT THE LAST GLACIAL TERMINATION

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**ABSTRACT.** There is a growing database of radiocarbon ( $^{14}\text{C}$ ) reconstructions from biogenic carbonate taken from marine sediment cores being used to investigate changing ocean circulation and carbon cycling at the end of the last great ice age. Reported here are  $^{14}\text{C}$  results from a marine core taken in the Makassar Straits of the western equatorial Pacific that was intended to test whether there was evidence of geologic carbon release to the ocean during the glacial termination. A thorough investigation of planktic and benthic  $^{14}\text{C}$  ages with stable isotopes and CT-scans revealed extensive burrowing in the upper 2 m of the core that displaced younger sediments downward by more than half a meter into the glacial section of the core. The vertical displacement is evident in both planktic and benthic fossils. However, the extent of displacement and the stratigraphic disturbance became evident only after multiple measurements of different species and genera. A CT-scan prior to sampling would be an effective screening tool to avoid sampling problem cores such as this.

**KEYWORDS:** isotope analysis, mysterious radiocarbon anomalies.

### INTRODUCTION

Considerable effort and expense have been devoted to reconstructions of radiocarbon activity ( $\Delta^{14}\text{C}$ ) of biogenic carbonates from marine sediments to evaluate how the global-scale overturning circulation responded to climate changes in the past. This is particularly true for the interval spanning the end of the last glacial maxima and the onset of deglaciation (18–14 kyBP) when the radiocarbon activity of the ocean and atmosphere fell by  $\sim 190\%$  while the production rate of radiocarbon did not decrease correspondingly (Laj et al. 2002; Hain et al. 2014). These contrasting observations led to the term “Mystery Interval” (Broecker and Barker 2007; Broecker 2009). And when considering how to reconcile these two opposing observations, it initially appeared there were only two plausible explanations, both entailing a change in the residence time of waters within the Ocean. The first hypothesis called upon enhanced bottom water stratification and the isolation of an abyssal water mass that accumulated respired metabolic carbon during glaciations (Toggweiler 1999) and then the aged,  $^{14}\text{C}$ -depleted abyssal waters were ventilated during the Mystery Interval (Broecker 2009). But after considerable effort, no such isolated abyssal water mass has been documented from glacial age sediment records (Broecker et al. 2004; Broecker and Clark 2010; Hain et al. 2011; Keigwin and Lehman 2015; Zhao et al. 2018). The second hypothesis calls for an enhanced biological pump during glaciations and an overall slow-down of ocean overturning. This would lead to a net accumulation of respired carbon and longer deep-water residence times during glaciations. Then during deglaciation, as ventilation rates increased, the residence time of deep water decreased (Sigman and Boyle 2000; Anderson et al. 2009, 2019; Kwon et al. 2011; Jacobel et al. 2019; Menviel et al. 2018). This hypothesis makes specific predictions about  $\Delta^{14}\text{C}$  change in the ocean during the deglaciation. It predicts that the  $\Delta^{14}\text{C}$  of deep waters throughout the ocean would increase as older ( $^{14}\text{C}$ -depleted) waters from the glacial ocean were replaced by younger

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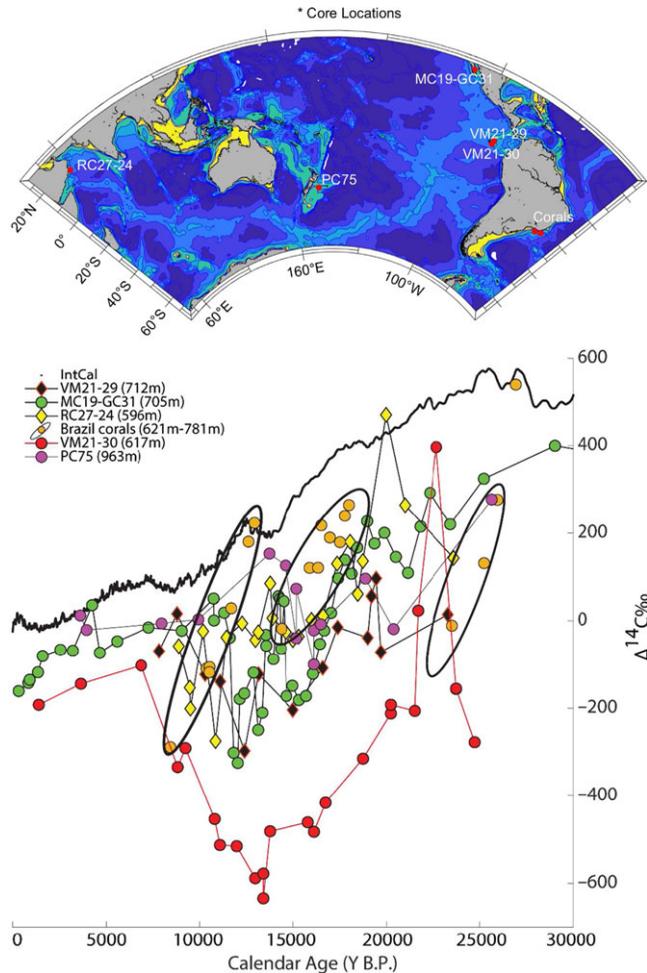


Figure 1 Upper panel is a site location map of the MD98-2164 core and other shallow-intermediate depth cores from previous studies that document benthic  $\Delta^{14}\text{C}$  excursions at the last glacial termination (lower panel), Table 2.

waters at the onset of deglaciation, (Huiskamp and Meissner 2012; Menviel et al. 2018). This hypothesis also predicts that the  $\delta^{13}\text{C}$  of dissolved inorganic carbon in deep waters would increase as  $^{13}\text{C}$ -depleted respired carbon is replaced by better-ventilated waters (Menviel et al. 2018).

While these ocean circulation hypotheses continue to be investigated, an alternative hypothesis has been put forth that calls upon release of “old” geologic carbon to the ocean and atmosphere during the late glacial and early deglaciation (Stott and Timmermann 2011). Evidence in support of this hypothesis includes large  $\Delta^{14}\text{C}$  excursions during the last deglaciation (Figure 1). These excursions have been identified in each ocean basin (Stott et al. 2009, 2019a, 2019b; Mangini et al. 2010; Stott and Timmermann 2011; Ronge et al. 2016; Rafter et al. 2018). But there are vast portions of the ocean that have not been explored. Hence, it is not yet clear how extensive these deglacial  $\Delta^{14}\text{C}$  excursions were and therefore, how much “old” carbon was released to the oceans

during the late glacial and early deglaciation. For this reason, efforts are underway to investigate other locations where geologic carbon may have been released to the oceans, including sites in the western equatorial Pacific, which is a geologically active region with numerous hydrothermal and volcanic sources that could contribute  $^{14}\text{C}$ -depleted carbon to the ocean.

In 1998 a coring cruise with the Marion Dufresne set out to obtain a suite of cores in the western Pacific, including sites within the Indonesian Archipelago. The original goal of the endeavor was to investigate the history of the Indonesian Throughflow during the Pleistocene using geochemical tracers to assess whether there was a change in the exchange of waters between the Pacific and Indian Oceans. The exchange of upper ocean waters between the Pacific to the Indian Ocean plays an important role in maintaining continuity in exchange of energy, mass and chemical constituents between ocean basins. For that study a suite of sediment cores was collected from shallow/intermediate water depths between 600 and 1000 m within the Indonesian Archipelago. And because these cores are located in the volcanically active Indonesian region, they are also ideally suited for investigating the history of  $\Delta^{14}\text{C}$  change and the potential role that geologic sources of carbon had on the carbon cycle during the last glacial cycle.

Studies of marine sediments typically begin by developing a stable oxygen isotope stratigraphy from planktic or benthic foraminiferal calcite taken from discrete horizons in a core. The downcore stable isotope values are then compared to well-established marine composite records (standard curves) of planktic or benthic  $\delta^{18}\text{O}$  that have been chronologically aligned to U/Th dated speleothem  $\delta^{18}\text{O}$  records or ice core records (Lisiecki and Stern 2016). But comparing a sediment core's stable isotope stratigraphy to a standard curve leaves uncertainty about a core's stratigraphic continuity or integrity. This is because sediment disturbances, missing sediments (hiatuses) may be undetectable from these comparisons alone. Radiocarbon data of biogenic constituents such as foraminifera may be a useful tool for evaluating a core's stratigraphic integrity. At the same time, these are costly measurements and when the purpose of making the  $^{14}\text{C}$  measurements is to explore whether there was a radiocarbon anomaly at the glacial termination, it is also possible that what may appear to be a  $^{14}\text{C}$  excursion is in fact, an artifact of core disturbance. This becomes clear only after developing a stable isotope stratigraphy and making numerous  $^{14}\text{C}$  measurements. In the present study an example is presented that illustrates how important it is to thoroughly investigate whether the stratigraphy of a core has been disrupted by post depositional processes such as large burrowing, which can displace sediments.

## STUDY SITE AND METHODS

In 1998 core MD9821-64 was collected in the Makassar Strait (Figure 1) (6.64°S, 119.42°E; 719 m water depth). The core was split into two halves. One half was used for sampling, the other archived. Sediment samples were taken at 5-cm intervals. Each sample was disaggregated in a buffered sodium hexametaphosphate solution and then washed over a 63 $\mu\text{m}$  screen to remove the fines. The >63 $\mu\text{m}$  fraction was then dried at low temperature. After drying the samples were weighed and stored in labeled vials. In April of 2010 a stable isotope stratigraphy was developed for the MD98-2164 core by analyzing samples of ~20 planktic foraminifer *Globigerinoides ruber* (white) (>250  $\mu\text{m}$  size fraction) picked from samples at 20–40-cm intervals in top two core sections. Prior to analysis the *G. ruber* samples were sonicated in distilled water for several seconds to remove fine debris and then dried at low temperature. The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  was measured on a Micromass Isoprime dual inlet mass spectrometer with carbonate device located at the University of Southern California in April 2010. A standard

calcite (Ultiss) was measured in the same system along with the foraminiferal samples. Average precision for these standards was  $<0.15\%$  for both oxygen and carbon. All stable isotope results are reported in ‰ relative to VPDB standard. Single specimens of *G. ruber* and *Globigerinoides sacculifer* ( $>250$  mm, no final sac) were also analyzed from 4 samples (11 cm, 181 cm, 191 cm and 195 cm). These specimens were cleaned using the same method as the multi-specimen samples. The Ultiss standard was run with these samples at weights similar to that of the single specimens ( $\sim 20$   $\mu\text{g}$ ). The precision for these small standard samples was also  $<0.15\%$ .

Between December 2009 and July 2010 planktic and benthic foraminifera were picked for radiocarbon analysis to assess whether there were changes in the surface to intermediate depth  $^{14}\text{C}$  age difference at the last glacial termination. Similar studies using cores from the eastern equatorial Pacific have documented large benthic-planktic (B-P)  $^{14}\text{C}$  age increases at the last glacial termination (Stott et al. 2009). Using the stable isotope stratigraphy as a guide, samples were selected at 10–20-cm intervals, starting from the 3-cm interval down to the  $\delta^{18}\text{O}$  maxima at 199 cm. In some samples the benthic foraminifer *Oridorsalis* sp were large enough to be analyzed individually. Bivalve shells and Gastropod specimens were also analyzed from several intervals. These samples were cleaned in the same way as the stable isotope samples. After cleaning and weighing the samples were submitted to the Keck Carbon Cycle AMS Laboratory at the University of California Irvine. The  $^{14}\text{C}$  ages are summarized in Table 1 in the chronologic order in which they were analyzed.

In August 2010 the top two sections of the core (half round tubes) were passed through a computed tomography scan (CT-scan) that combines X-ray measurements taken at different angles to produce a cross-sectional visualization of the internal structures of the core. This technique visualizes relative differences in sediment density and thus, is useful for characterizing core disturbances created by burrowing organisms.

## RESULTS AND DISCUSSION

The initial suite of *G. ruber*  $\delta^{18}\text{O}$  measurements (Figure 2) document two interglacial to glacial transitions corresponding to marine isotope stages 1 and 2 (0–200 cm) and stages 4 and 5 (750–900 cm). The magnitude of change between the warm interglacial stage 1 and the colder glacial stage 2 is  $\sim 2\%$  and very close to other *G. ruber*  $\delta^{18}\text{O}$  records developed from higher deposition rate cores from the western Pacific (Stott et al. 2002, 2004, 2007; Saikku et al. 2009). There is no indication of a break in the glacial to interglacial  $\delta^{18}\text{O}$  stratigraphy except a sample at 141 cm that has a slightly higher  $\delta^{18}\text{O}$  value than the sample at 161 cm. The stable isotope stratigraphy indicates the last glacial maximum occurs at  $\sim 199$  cm. Using the 199 cm sample as a chronologic datum implies an average sedimentation rate of  $\sim 10$  cm/kyr for the top 2 m of the core. With these results in hand it appeared appropriate to proceed with the second phase of the study, to develop planktic and benthic  $^{14}\text{C}$  ages to investigate whether there was increased benthic-planktic  $^{14}\text{C}$  age differences at the glacial termination as seen in other shallow-intermediate depth cores (see Table 2).

An initial suite of  $^{14}\text{C}$  measurements was conducted on multi-specimens of the planktic species *Globigerinoides sacculifer* and the benthic genus *Oridorsalis* (Figure 3a). This included 4 analyses of individual *Oridorsalis* sp specimens that were large enough for analysis. The planktic  $^{14}\text{C}$  ages appeared to confirm the stratigraphic ages inferred from the *G. ruber*  $\delta^{18}\text{O}$  stratigraphy. The *G. sacculifer*  $^{14}\text{C}$  age at 199 cm of 19,030 years is consistent with

Table 1 MD9821-64 <sup>14</sup>C results.

Depth (cm)	Fossils	Date analyzed	Weight (mg)	Planktic <sup>14</sup> C age (year)	Benthic <sup>14</sup> C age (year)	Error (yrs)	Accession
3	<i>Oridorsalis</i>	Dec. 11, 2009	3.51		2180	15	71595
3	<i>G. sacculifer</i>	Dec. 11, 2009	6.313	1730		20	71596
11	<i>Oridorsalis</i>	Dec. 11, 2009	4.501		2660	20	71597
11	<i>G. sacculifer</i>	Dec. 11, 2009	6.742	2035		20	71598
61	<i>Oridorsalis</i>	Dec. 11, 2009	6.637		4940	20	71599
61	<i>G. sacculifer</i>	Dec. 11, 2009	8.828	4670		15	71600
65	<i>Oridorsalis</i>	Dec. 11, 2009	6.62		5260	25	71601
65	<i>G. sacculifer</i>	Dec. 11, 2009	8.776	4600		20	71602
71	<i>Oridorsalis</i>	Dec. 11, 2009	5.946		4905	20	71603
71	<i>G. sacculifer</i>	Dec. 11, 2009	7.311	4625		15	71604
101	<i>Oridorsalis</i>	May 12, 2010	3.17		8010	25	77272
101	<i>Oridorsalis</i> (A)	May 12, 2010	1.184		8150	60	77273
101	<i>Oridorsalis</i> (B)	May 12, 2010	1.254		7055	45	77274
101	<i>G. sacculifer</i>	May 12, 2010	7.352	8060		20	77275
111	<i>Oridorsalis</i>	May 12, 2010	4.109		7450	20	77276
111	<i>G. sacculifer</i>	May 12, 2010	6.749	7075		20	77277
121	<i>Oridorsalis</i>	May 12, 2010	2.701		12125	45	77278
121	<i>G. sacculifer</i>	May 12, 2010	6.708	9905		25	77279
141	<i>Oridorsalis</i>	May 12, 2010	2.616		13240	50	77280
141	<i>G. sacculifer</i>	May 12, 2010	5.454	13090		40	77281
161	<i>Oridorsalis</i>	May 12, 2010	1.576		14250	110	77282
161	<i>G. sacculifer</i>	May 12, 2010	5.97	14885		45	77283
199	<i>Oridorsalis</i>	May 12, 2010	2.083		25100	310	77284
199	<i>Oridorsalis</i> (A)	May 12, 2010	1.933		21290	270	77285
199	<i>Oridorsalis</i> (B)	May 12, 2010	1.72		22440	320	77286
199	<i>G. sacculifer</i>	May 12, 2010	3.832	19030		110	77287
101	<i>N. dutertrei</i>	June 1, 2010	7.691	8595		20	78031
101	<i>G. sacculifer</i>	June 1, 2010	8.345	7820		20	78032
101	<i>Oridorsalis</i>	June 1, 2010	2.197		8480	40	78033
101	<i>Cibicides</i>	June 1, 2010	2.119		7995	45	78034
141	<i>N. dutertrei</i>	June 1, 2010	9.503	14685		35	78035
161	<i>N. dutertrei</i>	June 1, 2010	7.682	15730		60	78036
171	<i>N. dutertrei</i>	June 1, 2010	9.411	18435		50	78037
171	<i>G. sacculifer</i>	June 1, 2010	7.835	18100		80	78038
171	<i>Oridorsalis</i>	June 1, 2010	2.788		20000	160	78039
181	<i>N. dutertrei</i>	June 1, 2010	6.844	19370		70	78043
181	<i>G. sacculifer</i>	June 1, 2010	6.919	19210		70	78044
181	<i>Oridorsalis</i>	June 1, 2010	2.804		18890	170	78045
181	<i>Oridorsalis</i> (A)	June 1, 2010	5.134		19970	80	78046
191	<i>N. dutertrei</i>	June 1, 2010	9.08	17195		40	78047
191	<i>G. sacculifer</i>	June 1, 2010	8.131	12320		40	78048
191	<i>Oridorsalis</i>	June 1, 2010	5.491		16900	60	78049
191	Gastropod	June 1, 2010	21.835		18375	50	78050
195	<i>N. dutertrei</i>	June 1, 2010	7.887	17100		50	78051

Table 1 (Continued)

Depth (cm)	Fossils	Date analyzed	Weight (mg)	Planktic $^{14}\text{C}$ age (year)	Benthic $^{14}\text{C}$ age (year)	Error (yrs)	Accession
195	<i>G. sacculifer</i>	June 1, 2010	7.322	11325		30	78055
195	<i>Oridorsalis</i>	June 1, 2010	3.815		15120	70	78056
195	Bivalve	June 1, 2010	1.441		19580	270	78057
199	<i>N. dutertrei</i>	June 1, 2010	6.29	20450		100	78058
199	Bivalve	June 1, 2010	2.112	20340	190	78059	
81	<i>Oridorsalis</i>	Jul. 04, 2010	5.368		6380	20	79027
81	<i>G. ruber</i>	Jul. 04, 2010	5.09	5255	15	79028	
81	<i>G. sacculifer</i>	Jul. 04, 2010	9.866	5155		15	79029
191	<i>G. ruber</i>	Jul. 04, 2010	6.678	17270	60	79030	
191	<i>G. sacculifer</i>	Jul. 04, 2010	6.288	14050		35	79031
191	<i>G. sacculifer</i> (1)	Jul. 18, 2010	3.3	13790		35	79555
191	<i>G. sacculifer</i> (2)	Jul. 18, 2010	3.3	13330		60	79556
195	<i>G. sacculifer</i> (1)	Jul. 18, 2010	3.5	12265		35	79557
195	<i>G. sacculifer</i> (2)	Jul. 18, 2010	3.5	12280		40	79558

Note: Fossil names followed by (A) or (B) are individual specimen. Fossil names followed by (1) or (2) were replicate, multi-specimen samples. All results have been corrected for isotopic fractionation according to the conventions of Stuiver and Polach (1977), with  $\delta^{13}\text{C}$  values measured on prepared graphite using the AMS spectrometer at UCI.

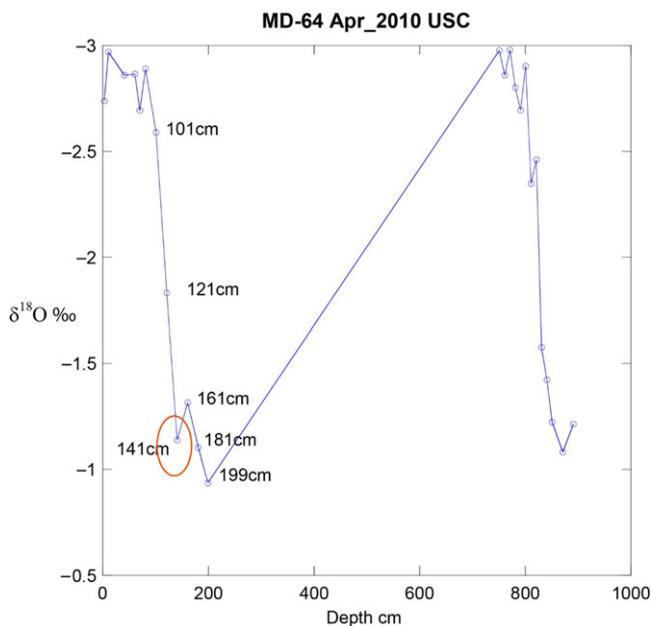


Figure 2 Multi-specimen  $\delta^{18}\text{O}$  ‰ values of *G. ruber* (white) from core MD98-2164.

Table 2 Shallow-intermediate depth sites shown in Figure 1.

Site	Latitude	Longitude	Water depth (m)	Author
VM21-29	1.0	-89.4	712	Stott et al. (2019a)
VM21-30	-1.2	-89.7	617	Stott et al. (2019a)
MC19-GC31	25.5	-111	705	Marchitto et al. (2007)
RC27-24	18.3	57.7	596	Bryan et al. (2010)
PC75	-44.2	-182	967	Stott et al. (2019)
Brazil corals	-22.5, -24.5	-40, -43	621–781	Mangini et al. (2010)

this being the last glacial maximum. At the same time, several observations stood out when comparing the benthic and planktic  $^{14}\text{C}$  ages. At the top of the core the B-P  $^{14}\text{C}$  ages are 450 and 625 years, close to modern sea water age contrast between the surface and 700–800 m. But the B-P  $^{14}\text{C}$  values for the 101 cm and 161 cm samples are reversed (-322 and -635 years, respectively). And even more striking, the B-P  $^{14}\text{C}$  age for the multi-specimen samples increase to 6070 years in the 199-cm sample. By contrast, the single specimen *Oridorsalis* to planktic age difference, is 3410 and 2260 years.

These initial results constituted a perplexing problem. The reversal of B-P  $^{14}\text{C}$  ages in two intervals might be indicative of a core disturbance and reworking of older material. At the same time, the large increase in B-P  $^{14}\text{C}$  ages at 199 cm was an intriguing indication that the core might also record a large benthic  $^{14}\text{C}$  excursion at the glacial termination like those seen at other sites (Figure 1). And the fact that the two individual benthic specimens at 199 cm have very different ages compared to the bulk specimen sample was also intriguing. It could mean that there was reworking of older materials into this horizon or, it could mean that there was variable input of local geologic “dead” carbon from nearby sources. For this reason, the next logical step was to evaluate whether the planktic foraminifera also contained mixed ages because planktic  $^{14}\text{C}$  ages should not be influenced by localized input of geologic carbon. However, planktic specimens are too small for individual  $^{14}\text{C}$  dating. Instead, a suite of planktic *G. sacculifer* and *G. ruber* were analyzed individually for  $\delta^{18}\text{O}$  in June of 2010 (Figure 4). The results from these analyses were even more perplexing. Among the individual *G. sacculifer*  $\delta^{18}\text{O}$  results at 191 cm and 195 cm there are values that are clearly indicative of early and late Holocene  $\delta^{18}\text{O}$  values. This is at odds with the benthic  $^{14}\text{C}$  ages at 199 cm that appeared to document much older glacial benthic ages, not younger ages. The stable isotopes and the radiocarbon results seemed to be giving very different results. And further perplexing was the fact that there are no *G. ruber*  $\delta^{18}\text{O}$  outliers, only the individual *G. sacculifer* exhibit “younger” outliers (Figure 4).

By the end of June 2010, a decision had to be made whether to proceed with the investigation. On one hand, the large increase in benthic  $^{14}\text{C}$  ages at 199 cm was an intriguing possibility that the core might document “old” carbon at the glacial termination. On the other hand, the fact that the *G. sacculifer*  $\delta^{18}\text{O}$  results contained what appeared to be “younger” ages in the 195 cm sample suggested that this portion of the core may be compromised in some way. The decision was made to submit a second batch of samples for  $^{14}\text{C}$  dating. This time the focus was only on the intervals between 101 and 199 cm. The samples included different species, including some bivalve specimens and a gastropod specimen (Table 1). This second batch also included two separate samples of *G. sacculifer* from the 191-cm and the 195-cm intervals. In this case

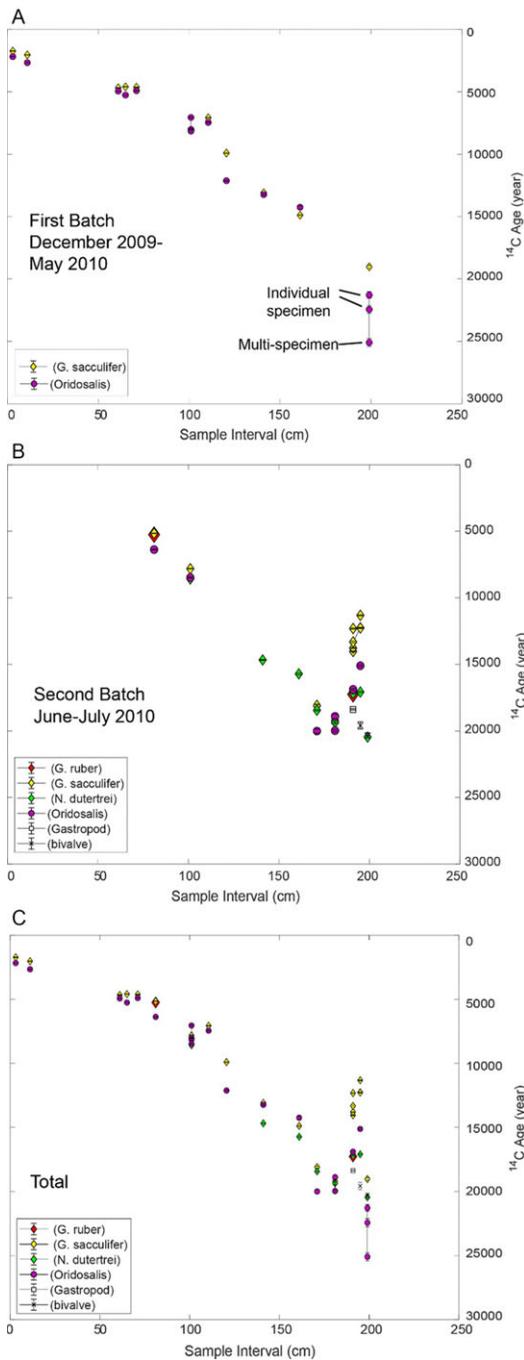


Figure 3 Panel A, the initial batch of  $^{14}\text{C}$  ages obtained for *G. sacculifer* and *Oridosalis* sp. Note the large age offset between the *Oridosalis* and *G. sacculifer* ages at the 199-cm horizon. Panel B is the second batch of benthic and planktic  $^{14}\text{C}$  ages. Note that in the second batch the ages from the 191 cm and 195 cm samples are much younger than the surrounding intervals, including the 199-cm horizon, just 4 cm deeper in the core. Panel C is all the data plotted together highlighting the anomalously “young” ages of specimens between 191 cm and 195 cm.

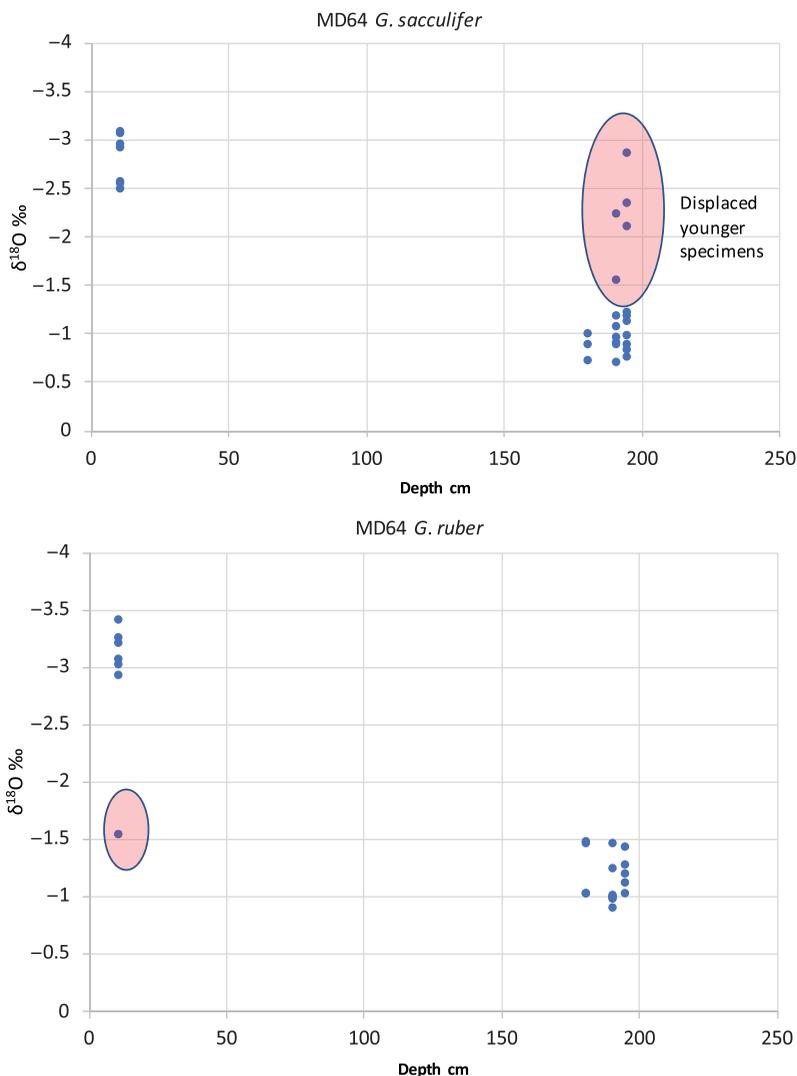


Figure 4 Upper panel is individual specimen  $\delta^{18}\text{O}$  values for *G. ruber*. Lower panel is individual  $\delta^{18}\text{O}$  values of *G. sacculifer* (no final sac). Note that in the 191-cm and 195-cm intervals approximately 10% of the individuals exhibit anomalously “young”  $\delta^{18}\text{O}$  values that are indicative of intervals higher in the core.

*G. sacculifer* specimens were split into two categories. Category (1) contained only pristine, unbroken tests. Category (2) specimens were less well-preserved, either because the specimens were slightly broken, abraded or dirtier. The reasoning was that perhaps there were two age groups that might be distinguishable based on their degree of preservation. The findings from the second batch are shown in Figure 3B.

The  $^{14}\text{C}$  results from the second batch clearly indicate that the interval centered between 190 and 200 cm of the core contains a mixture of specimens with widely varying ages. And importantly, the second batch of *G. sacculifer* returned ages that were very different from those from the first batch. The *G. sacculifer*  $^{14}\text{C}$  ages from the 191 cm and 195 cm are between 12,000 and 14,000 years and thus, are not glacial values whereas the first batch of

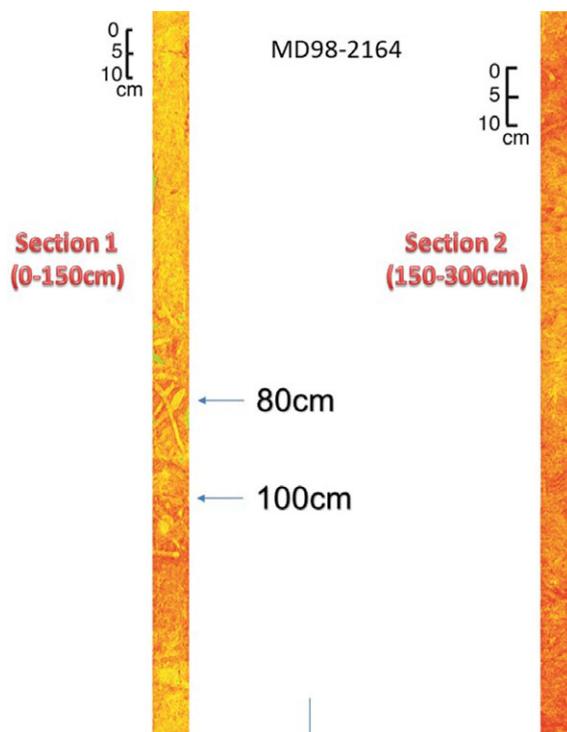


Figure 5 False color images of the CT-scans of the top two sections of core MD98-21064. The largest and most evident single burrows are evident between approximately 60 and 120 cm.

*G. sacculifer* from the 199-cm interval has a  $^{14}\text{C}$  age of 19,030 years and is glacial age. And there is no significant age difference between the Category (1) and Category (2) *G. sacculifer*. Both are anomalously “young”. The *Neoglobquadrina dutertrei* and *G. ruber* ages at 191 cm and 195 cm by contrast are much older than *G. sacculifer*. It is particularly striking that within 4 centimeters, the *G. sacculifer*  $^{14}\text{C}$  ages differ by as much as 7000 years. Furthermore, the bivalve shell and the Gastropod specimen both have late glacial/early deglacial ages and are not as anomalously young as are the *G. sacculifer* specimens. However, the *Oridorsalis* samples at 191 cm and 195 cm are much younger (16,900 and 15,120 years respectively) than the glacial age sample at 199 cm.

When all the  $^{14}\text{C}$  ages are plotted together (Figure 4C) it becomes evident that the entire core between approximately 60 cm and 200 cm contains a menagerie of mixed  $^{14}\text{C}$  ages. And most striking are the anomalously young ages in the 191–199-cm samples, particularly the *G. sacculifer* and *Oridorsalis* ages. These results imply that many specimens of *G. sacculifer* and *Oridorsalis* have been displaced downward from intervals higher in the sediment column and the displacement is more than 50 cm.

Having invested so much time and financial resources in this core it seemed appropriate to try to determine what process could possibly explain the strange array of radiocarbon ages, particularly the anomalously “young” ages at 191–195 cm. Bioturbation comes in many forms and has varying influences on the sediment mixing. Studies of excess  $^{234}\text{Th}$  and  $^{10}\text{Be}$  have even documented downward transport in modern sediments of as much as 26 cm

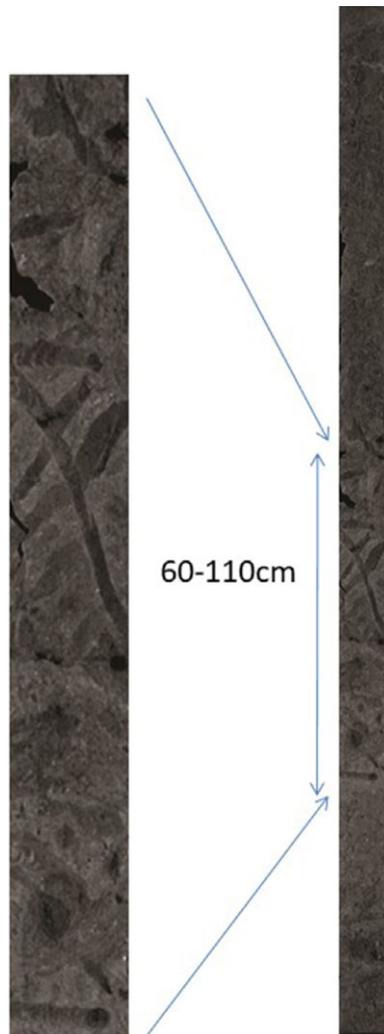


Figure 6 CT-scan zoomed in on the interval of section 1 with the largest and longest burrows. The largest burrows are over 2 cm in diameter and can be traced in the CT-scan for over 40 cm.

(Smith et al. 1997). But the radiocarbon results from the MD98-2164 core seem to imply that downward sediment transport exceeds more than half a meter. To evaluate whether downward burrowing might account for the anomalously “young” ages in the glacial section of the core, a CT-scan was performed on the core. The CT scans does indeed illustrate extensive burrows below 60 cm (Figure 5). In closeup view of the interval between 60 cm and 110 cm the burrows are very large. Some burrows are more than 2 cm in diameter and are lengthy (Figure 6). Single burrows can be traced in multilayer images (not shown) over 30–40 cm. It is therefore evident that at this location, benthic organisms have effectively corrupted the stratigraphic integrity of the core.

## FINAL THOUGHTS AND CONCLUSIONS

The results from this study highlight several lessons. The first is that if this study had ended after the first batch of  $^{14}\text{C}$  ages were obtained, the conclusions might have been completely different. The initial planktic  $^{14}\text{C}$  ages did not reveal anything unusual in the stratigraphy. And, the large B-P  $^{14}\text{C}$  age increase at 199 cm might have been mistaken for evidence of local input of “old” carbon. But after conducting the stable isotope measurements of single *G. sacculifer* specimens, it became clear that additional radiocarbon measurements were necessary to better characterize the  $^{14}\text{C}$  record of this core. Secondly, had *G. ruber* been chosen for  $^{14}\text{C}$  age dating instead of *G. sacculifer*, the results may also have been different. For reasons that are not immediately obvious the single specimen  $\delta^{18}\text{O}$  analyses and the  $^{14}\text{C}$  ages for *G. ruber* do not exhibit the same anomalously “young” values at 191–195 cm as do the *G. sacculifer* values. This is an issue that will require additional investigation. The lesson is that obtaining  $^{14}\text{C}$  ages for multiple species of foraminifera is important. This is not always possible where individual benthic foraminifer species are not abundant enough for single species analyses. In the western equatorial Pacific multispecies analyses and replicating observations from multiple closely associated cores proved valuable in validating the extremely  $^{14}\text{C}$ -depleted benthic foraminiferal records in the shallow-intermediate water depth cores at that location (Stott et al. 2019b). But it is clear that individual data points and even individual core records must be considered with some caution until more comprehensive records become available.

In the MD98-2164 core both benthic and planktic specimens have been displaced downward by as much as 50–60 cm. Presumably, burrowing could also move older sediments upward as well, which would produce what appears to be a  $\Delta^{14}\text{C}$  excursion like those seen in other cores. But burrowing moves both benthic and planktic specimens together, although not necessarily in the same proportion (e.g. *G. ruber* vs. *G. sacculifer*). Therefore, measuring multiple species or genera of both planktic and benthic fossils is an important way to distinguish between vertical displacement and what may be inputs of anomalously old carbon. And finally, CT-scans are a valuable and relatively inexpensive method for evaluating the integrity of a core. Had the CT-scans been conducted on the MD98-2164 core before sampling commenced the core would never have been sampled and a great deal of effort and expense would have been avoided. Unfortunately, CT scans may not be practical when sampling old cores that have dried and been heavily sampled.

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